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A pathway toward improving hydrologic predictions

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1 INTRODUCTION

In the aftermath of the Great Flood of 1993 in the Upper Midwest and the recent droughts in the western and south-eastern areas of the Nation, the National Weather Service (NWS) is committed to the development and implementation of an Advanced Hydrologic Prediction System (AHPS) capable of producing hydrologic forecasts with lead times of a few days to several months. Such forecasts will greatly improve the Nation's capability to take timely and effective actions to mitigate the effects of floods, and the forecasts will also provide significant improvements in the type and quality of hydrologic information that is used to manage the Nation's water resources (e.g., better management of the competing water demands between irrigation, fisheries, and hydropower).

The AHPS will build upon the following components:

1. partnerships with other water cooperators (federal, state, multi-state, quasi-governmental, and private sector organizations);
2. the existing NWS hydrologic forecasting infrastructure including the 13 NWS River Forecast Centers (RFC) and the NWS River Forecast System (NWSRFS), a very large software system used by RFC hydrologists to produce forecasts of time series of discharges and/or stages at selected locations (approximately 4,000), along the Nation's rivers; and,
3. the NWS Modernization which is providing enhanced scientific and technological components to support the AHPS.

The NWS Modernization is providing NWS RFCs with Advanced Weather Interactive Processing System (AWIPS) equipment, a powerful suite of networked computer workstations with graphic capabilities. The Modernization is also providing national coverage with approximately 140 NEXRAD WSR-88D Doppler radars which produce high resolution (space and time) precipitation estimates while utilizing gauge precipitation observations from networks such as the new Automated Surface Observing System (ASOS). The processing algorithms that produce the precipitation estimates are being enhanced to account for bright band effects and to improve the rain gauge bias adjustment, while future enhancements will address orographic effects and snow accumulation.

The fourth critical component of the AHPS is the Water Resources Forecasti System (WARFS). The WARFS initiative will provide additional resources to

1. make critical software enhancements to the NWSRFS;
2. develop a NOAA Hydrologic Data System (NHDS);
3. increase the use of short- to long-range weather and climate forecasts within t NWSRFS through appropriate hydrometeorological coupling algorithms;
4. calibrate and field-implement the advanced hydrologic/hydraulic models with the NWSRFS;
5. implement a snow estimation and updating system (SEUS) that provides gridd estimates of snow water equivalent; and,
6. provide more timely, accurate, and informative forecast products to governme and quasi-government water and emergency managers and to private sect intermediaries who provide value-added services to specific industries.

This paper focuses on the principal software enhancements and developmen provided under WARFS by giving a brief description of each system being enhanced well as the new systems being developed.

2 NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

The National Weather Service River Forecast System (NWSRFS) is a software syste (over 400,000 lines of computer code) consisting of many programs, which are used perform all steps necessary to generate river/stream discharge and stage forecasts (Frea et al., 1991). The system includes the Calibration System (CS), the Operation Forecast System (OFS), the Extended Streamflow Prediction (ESP) System, and th Interactive Forecast Program (IFP).

2.1 Calibration system

The CS performs the tasks needed to process historical hydrometeorological data and t estimate model parameters for a specific basin. The models simulate sno accumulation and ablation, calculate runoff, time distribute runoff from the basin to th basin outlet, and route streamflow through reservoirs and channel systems. Th NWSRFS is a modular system that allows the hydrologist to select from a variety c models and to configure them in a manner that is descriptive of the basin. All of th models are available to the Calibration, Operational Forecast, and ESP systems. As pa of the calibration procedure, for a particular basin, the simulated streamflow i statistically and visually compared to the observed streamflow to determine th necessary model parameter adjustments. The ideal model parameters are those wit which the model simulated streamflow most closely matches the observed streamflow The CS will be enhanced with capabilities for Graphical User Interface (GUI)-base interactive control of the hydrologic parameter calibration process within a multipl graphical display windows environment. This together with strategic use of a multi parameter random/shuffled evolution/ pattern search optimization algorithm wil significantly increase the efficiency of the calibration of hydrologic model parameters.

2.2 Operational forecast system

Once the models have been calibrated for a basin, they can be used operationally with real-time hydrometeorological data to forecast river flows and stages. The OFS contains three major components that are needed for operational river forecasting: Data Entry, Preprocessor, and Forecast. The Data Entry Component is a set of programs that transfer hydrometeorological data from a variety of sources to the observed data base. The Preprocessor Component reads raw station data, estimates missing data as required, and then uses these data to calculate mean areal time series of precipitation, temperature, and potential evapotranspiration for a particular basin. These processed time series are used by the Forecast Component to perform requested hydrologic and hydraulic simulations. The Forecast Component stores parametric data for the models, as well as information that describes the basin connectivity of the river system. In addition, the Forecast Component maintains an account of the current model states. These states describe the hydrologic condition of the basin, including the snow cover, soil moisture, and channel storage. They are needed as starting points for subsequent forecasts. Modeling components within the OFS will be enhanced; e.g., a hydrologic model will be provided with an appropriate spatially distributed structure (Lindsey 1993) and the dynamic routing model (Fread and Jin 1993) will be improved to account for the effects of multiple levee failures, dam failures, and sediment transport.

2.3 Extended streamflow prediction system

ESP is the portion of the NWSRFS which enables a hydrologist to make extended probabilistic forecasts of streamflow and other hydrological variables (Day 1985). ESP assumes that historical meteorological data are representative of possible future conditions and uses these as input data to hydrologic models along with the current states of these models obtained from the Forecast Component. A separate streamflow time series is simulated for each year of historical data using the current conditions as the starting point for each simulation. The streamflow time series can be analyzed for peak flows, minimum flows, flow volumes, etc., for any period in the future. A statistical analysis is performed using the values obtained from each year's simulation to produce a probabilistic forecast for the streamflow variable. This analysis can be repeated for different forecast periods and additional streamflow variables of interest. Short-term quantitative forecasts of precipitation and temperature can be blended with historical data to produce a more realistic transition in meteorological conditions, though this method is fairly simplistic at present. It is also possible to weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year. ESP allows flexibility in the streamflow variables which can be analyzed, the capability to make forecasts over both short and long time periods, and the ability to incorporate forecast meteorological data into the procedure. Because of the flexibility and conceptual basis of ESP, it has many applications, including water supply forecasts, flood outlooks, and drought analysis. The ESP will be enhanced to realistically account for the effects of reservoirs and flow diversions as it produces streamflow time series trace ensembles using multiple years of historical time series of precipitation and temperature as input to the OFS hydrologic/hydraulic modeling components. The forecaster, using new GUI-based multiple windows graphical display software, will statistically analyze the streamflow trace ensembles within specified future time windows to produce probabilistic streamflow forecasts.

2.4 *Interactive forecast program*

The major components that make up the IFP are:

1. the hydrologic models in the NWS River Forecast System;
2. the X-window protocol available on scientific workstations running UNIX;
3. the X-toolkits available to provide building blocks for applications program interface development; and,
4. commercial off-the-shelf software for the development of graphical display and interactive program control modules (Page and Smith 1993).

The IFP allows the forecaster to use hydrologic expertise and judgment to develop a forecast while streamlining the tasks required to produce the forecast. The forecaster can interactively make changes to the parameters, data, or current conditions used for hydrologic simulation and quickly see the results of those changes. These changes can be categorized into those affecting time series and those affecting a specific hydrologic model. A graphical user interface allows any required changes to be made with a minimum of effort. Graphical displays consist of those for user orientation and for data presentation. An example of a user orientation display is a schematic of the forecast points being modeled in the current IFP session; the display shows the connectivity of the points and the current state of the streams in each forecast area. Examples of data presentation are model inputs and simulation results presented in graphical plot displays. The IFP is being continuously enhanced as experience in using it for real-time hydrologic forecasting accumulates.

3 NOAA HYDROLOGIC DATA SYSTEM

The NOAA Hydrologic Data System (NHDS) will provide the nucleus of capabilities required by the AHPS to handle the integration of real-time/historical station and gridded data, and model generated (forecast) outputs. The data sets will be large having sizes comparable with up to 50 years, at temporal resolutions of hourly to daily for gridded (50,000 to 150,000 grid points at resolutions as small as 2 km) estimates of surface hydrometeorological parameters such as precipitation, temperature, snow water equivalent, and evapotranspiration; and, time series of point estimates for parameters such as river flow, river level, and reservoir discharge. NHDS will access, assimilate, analyze and maintain the required data and information. The information maintained by the NHDS spans the time domain from historical to real-time, and spans the quality domain from observed, or raw data, to high quality derived products. The data handled by the NHDS will be acquired from a variety of sources which also provide data which span the quality and time domains. Characteristics of current and potential operational and archive data sources are now being identified, and plans and techniques for acquisition of these data by the NHDS are being developed.

The data storage and retrieval system will take advantage of recent advances in computer technology; it will enable users to obtain recent historical data, add it to the historical data archive, and make it readily available to users. This system should take advantage of recent advances in computer technology for the storage and retrieval of data. A user-friendly interactive system will enable users to graphically display stations with specific types of data and station index information (e.g., period of record, reporting interval, history of moves, availability of data, and quality of data) for easy selection of stations for retrieval. An archival system for real-time data will enable these data to be used for verification (post-analysis) and re-calibration as well as continual updates to the historical data used to drive the ESP simulations. These data will increase the density of the network and thereby provide improved spatial estimates. In addition, these data will help to identify biases between the real-time and climatic networks.

A database management system (DBMS) will store and manage historical observed and processed data for development, calibration, and ESP. The DBMS takes advantage of recent advances in operating system and database technology (e.g., Geographic Information Systems (GIS), relational databases and object-oriented databases). Recent advances in GIS technology will enable users to better analyze and visualize spatial data. Basic data sets (e.g., elevation, soils, land use, boundaries, rivers, seasonal precipitation, seasonal evapotranspiration, and vegetation) will be available for display and analysis. The DBMS will store time series data; i.e., raw data, estimated data, and multiple copies of processed data with the appropriate flags for identification.

The large volumes of data will require analysis techniques which are relatively automated with minimal manual intervention. The advanced mathematical/statistical analyses to be performed upon the data involve the production of high quality estimates of fields and time series of hydrometeorological physical and derived elements using multivariate analysis techniques. The data analysis required in preparation for hydrologic model calibration is critical. This includes station selection, data quality control, estimation of station means, consistency analysis (including the assessment and/or replacement of missing data), and estimation of station weights. Interactive programs with graphical displays of outputs will be used to perform these steps. Historical data analysis in mountainous areas will be improved and made more efficient by integrating hydrologic, mathematical, and statistical data analysis procedures with GIS capabilities. Mathematical/statistical techniques will be implemented for data quality control (e.g., singular value decomposition and optimal interpolation).

4 HYDROMETEOROLOGICAL COUPLING TO ESP SYSTEM

The existing ESP procedure assumes that meteorological events which occurred in the past are representative of events which may occur in the future. Using these data, a separate streamflow time series is simulated for each year of historical data using the current soil moisture and streamflow conditions as the starting point for each simulation. Before an ESP analysis is performed upon these potential future streamflow trace ensembles, the forecaster can subjectively weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year. Since subjective weighing is unreliable, a forecaster usually assigns an equal weight for each simulated year. However, this approach disregards the relative importance of the recent past, present, and predicted future meteorological and climatological states. One approach involves searching for possible correlations of streamflow with large scale phenomenon such as El Niño (Georgakakos and Guetter 1995); however, this may be only meaningful in restricted areas of the Nation. The need for objective procedures to assign weights to each simulation is the basis for the development of a hydrometeorological coupling procedure for ESP analyses which will also take advantage of the growing skill in short-to long-range weather and climate forecasts. Another approach to such coupling involves the development of objective techniques for the assignment of weights to the individual traces included in the ensembles analysis based on multiple streamflow simulations using 25 or more years of historical records. Probabilistic streamflow forecasts can then be developed using mathematical/statistical analyses upon the traces obtained for each year of data. These analyses can be performed for different forecast periods and additional hydrologic variables of interest.

Meteorological/climatological forecasts would be the most useful if detailed quantitative precipitation forecasts (QPFs) could be directly input to streamflow prediction models. Unfortunately, current QPF models and procedures do not consistently provide sufficiently accurate values for direct input to hydrologic models. Although current QPF products provide generalized guidance information indicating rainfall amounts and locations of rain-fall areas, they generally do not provide the necessary detail and accuracy required for assigning QPF values to individual watersheds, especially for time windows beyond 12 to 24 hours.

In the absence of sufficiently precise meteorological forecasts, enhanced ESP ensemble analyses approaches will be developed to objectively extract the skill contained in the meteorological forecasts through coupling of the historical time series of precipitation with the precipitation forecasts for the current year (Ingram et al. 1995). This coupling can be achieved through application of a class of mathematical procedures (Bretherton et al. 1992) called singular value decomposition (SVD). A measure of relative confidence in the QPF information for various time horizons will be applied as part of the pattern series correlation to arrive at the relative weights for use in the ESP ensemble analyses.

5 SNOW ESTIMATION AND UPDATING SYSTEM

The Snow Estimation and Updating System (SEUS) is being developed to provide improved snow water equivalent estimates using existing ground-based and airborne observed snow data to better estimate the snowpack conditions using NWSRFS to make extended water supply, hydropower, irrigation, and flood mitigation forecasts. The system ingests observed snow water equivalent data in real time, calculates a standardized deviate of each observation, interpolates the deviates into a gridded field and develops an estimated snow water equivalent field by combining the standardized deviate field with a long-term mean snow water equivalent field. The gridded snow water equivalent estimates incorporate the spatial variability of the snowpack induced by the orographic effect in the West.

The SEUS uses the power of a geographic information system to store, analyze and display the spatial data necessary to perform the estimation. The system is designed to develop snow water equivalent on a basin basis and provide average snow water equivalent over a basin or subarea. To accomplish these tasks, SEUS consists of three components (McManamon et al. 1993): a calibration component, an operational component and an updating component. The calibration component analyzes historical snow observation data and develops the parameters needed to estimate gridded snow water equivalent. The operational component accesses real-time data and takes advantage of the parameters developed in the calibration component to determine gridded snow water equivalent. The updating component modifies the existing snow water equivalent states of the conceptual snow model within NWSRFS based on the weighted contributions of the simulated model snow states and the estimates of the snow states developed using the snow observations. The weighting for each estimate reflects the relative uncertainty of the estimate due to such factors as model bias and measurement error.

The point snow water equivalent data are interpolated into a gridded product using data derived during the calibration step. The average snow water equivalent estimates over subareas within each basin are used to update the snow water equivalent states of the conceptual snow model. The same methodology is used to generate gridded snow water equivalent over uncalibrated basins areas by applying parameters developed for calibrated basins over areas with analogous characteristics.

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